MEASUREMENT OF PROTON-INDUCED RADIATION IN ANIMAL TISSUE*

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Hadron therapy, because of the dosimetric and radiobiological advantages, is more and more often used in tumour treatment. This treatment method leads also to the radioactive effects induced by energetic protons on nuclei. Nuclear reactions may lead to the production of radioactive isotopes. In the present experiment, two animal (human-like) tissue samples were irradiated with 60 MeV protons. Gamma-ray spectroscopy and lifetime measurements allowed identifying isotopes produced during the irradiation, *e.g.* ^{18}F and ^{34m}Cl.

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1. Introduction

The present project is motivated by insufficient knowledge about long-lived radioisotopes, which can be produced during proton therapy [1, 2]. Except for the high linear transfer of energy, the efficiency of particle therapy can also be augmented by induced radioactivity. During radioactive decays, different particles (which deposit energy in surrounding tissues) are emitted and synergistic effect can occur. The efficiency of tumour cell killing by mixed radiation is higher than that for a separated radiation.

The main goal of the project is an appraisal of dose from the induced radioactivity deposited in irradiated and surrounding tissues. Gamma-ray spectroscopy and lifetime measurements can be used to determine the amount of isotopes produced during irradiation. To provide the consistency of the result, the Geant4/GATE [3, 4] simulations are used.

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2. Materials and methods

The experiment was performed at the Institute of Nuclear Physics of the Polish Academy of Sciences in Kraków. The proton beam accelerated to 60 MeV (proton energy for eye therapy) was provided by the AIC-144 isochronous cyclotron and the samples were irradiated with doses in the range from 30 Gy to 500 Gy. To achieve a homogeneous distribution of the dose in the sample, a technique called Spread Out of the Bragg Peak [5] was used.

Liver and bone samples were irradiated. These samples are composed of not only light nuclides such as hydrogen, carbon or oxygen, but also of heavier ones, like potassium or iron. Furthermore, those tissues have an ability to accumulate much heavier elements. The pig liver was chosen because of its composition, which is similar to the human one, and its easy availability. The samples of bone were prepared from a beef meal with a few additional drops of water. Liver and bone samples were frozen using liquid nitrogen so that they kept their shape during irradiation by a horizontal beam.

3. Results

The energy spectrum of gamma rays emitted by the beef bone irradiated with the dose equal to 250 Gy is presented in Fig. 1. The spectrum was measured using a HPGe detector. There are several notable peaks: the 511 keV β^+ annihilation peak, 147 keV, 1157 keV and 2127 keV. Except for the 1157 keV line (^{44}Sc), they originate from ^{34m}Cl [6].

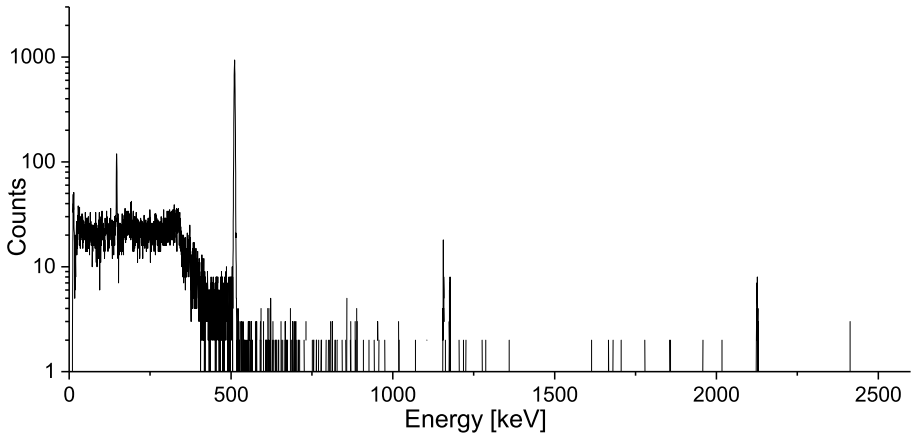

Fig. 1. Gamma-ray energy spectrum of a bone irradiated with a dose of 250 Gy, measured with a HPGe detector placed in a low-background lead shield. The measurement started 2 hours after irradiation and lasted for 2 minutes.

Figure 2 presents the gamma-ray energy spectrum of an irradiated pig liver measured using a $LaBr_3$ scintillator detector. There are three notable peaks: the annihilation peak, 683 keV and 1460 keV. Three main sources of the annihilation peak are β^+ decays of ^{11}C, ^{13}N and ^{18}F, which is confirmed by the time spectrum exhibiting the three decay constants of those isotopes. The line at the energy of 1460 keV originates from the natural background (^{40}K). The peak with energy around 680 keV has no confirmed origin. The most probable source of this γ-ray line is ^{204}At because of the energy and intensity of the gamma-ray line and a similar half-life. For the further calculation, it was assumed that this isotope is the source of the observed radiation.

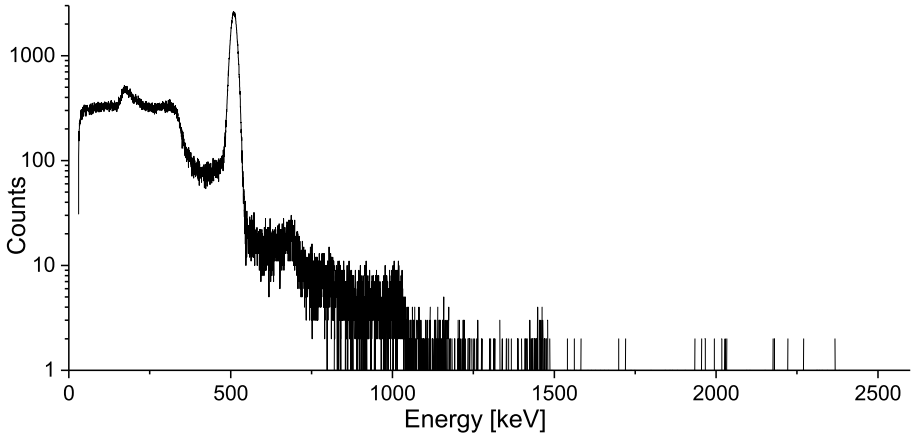

Fig. 2. Gamma-ray energy spectrum of liver irradiated with a dose of 500 Gy measured with a $LaBr_3$ detector. The measurement started 10 minutes after irradiation and lasted for 100 seconds.

To estimate the dose from proton-induced radioactive isotopes, Monte Carlo simulations were performed using the Geant4/GATE package [3, 4]. In the simulation, the radioactive isotopes were located in the centre of a water sphere of 4 cm diameter. Figure 3 presents examples of spatial dose distributions obtained for two isotopes, ^{11}C (left) and ^{34m}Cl (right).

In order to calculate the dose delivered to the surrounding tissue from the observed radioisotopes, the irradiated sample volume and the total received dose were taken into account (see Table I).

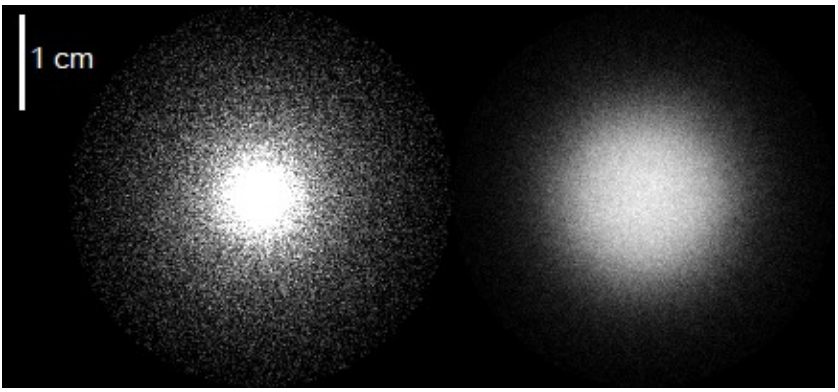

Fig. 3. Spatial projections of dose distribution in water from point-like sources of ^{11}C (left) and ^{34m}Cl (right).

TABLE I

Dose from notable radioisotopes.

Radioisotope	Dose $\left[\mathrm{Gy_{isotope}/Gy_{therapy}\ cm^3}\right]$	Tissue
^{11}C	8.7×10^{-9}	Liver
^{13}N	1.9×10^{-9}	Liver
^{18}F	4.3×10^{-11}	Liver
^{34m}Cl	3.9×10^{-9}	Bone
^{204}At	7.8×10^{-10}	Liver

4. Conclusions

Based on the presented results, there is no indication that the induced radioactivity, created during eye proton therapy, changes significantly the global therapeutic effects. Some curious gamma-ray lines were observed, for example that at 683 keV, that should be studied further. In order to test the local effects of the induced radioactivity, radiobiological studies should be performed.

5. Forthcoming research

During particle therapy of deeply located tumours, a more energetic proton beam is used. Therefore, an extension of the present experimental activities to higher beam energies is needed. The experiment will be continued also for other types of therapeutic beams, such as carbon ions and neutrons.

The last step of this project will explore the influence of radioactivity induced in the irradiated tissue on the surrounding non-irradiated cells.

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